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# X-Ray Optics

**Final** Technical Report *per HRS*  
for the period  
**15 Oct 86 - 29 Sep 89**  
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## Introduction

The Center for X-Ray Optics has continued in its dual roles of demonstrating the capabilities and usefulness of the x-ray and ultraviolet regions of the electromagnetic spectrum and developing instrumentation and techniques to make these capabilities widely and readily available. The University Research Initiative contract enabled the Center to maintain its student training effort, with both graduate and undergraduate student assistants continuing their contributions to the Center's research projects. This report will be supplemented with our "1989 Annual Activities Report" when it becomes available in spring 1990.

## Progress

Progress is reported here in five areas of x-ray science and technology as described below. The involvement and contribution of the student assistants in this work is then described.

### *Application of Diffractive X-Ray Optics*

We have already achieved soft x-ray microscopy resolutions of 500 Å. During the past year we fabricated zone plates with outer zone widths as small as 300 Å, and we are hoping to achieve images resolved to 400 Å.

### *Multilayer Mirrors for X-Ray Imaging*

We have been making mirrors for reduction x-ray lithography at 145 Å, x-ray laser cavity mirrors for wavelengths from 44.8 Å to 206 Å a hard x-ray (1 Å) microprobe for materials science and phase-transition studies, as well as other coatings for high thermal loading synchrotron radiation applications.

### *Multilayer Mirrors for Free Electron Lasers*

We continue to study detailed materials science issues associated with deep UV-FEL mirrors and cavity extraction techniques.

### *Soft X-Ray Imaging and Spectroscopy of Biological Material*

We continued the development of microscopy techniques for the life and physical sciences. This included studies of subcellular structure and function, surface and materials science studies, and preliminary excursions into x-ray nanolithography.

### *Simulations of Extreme Ultraviolet Optical Systems*

Progress was made on extending a computer program for x-ray tracing to include radiation from insertion device sources (undulators and wigglers) of synchrotron radiation.

## **Student Work**

**Yan Wu** is a graduate student in physics at UC Berkeley approaching completion of his studies. His specific thesis area involves x-ray scattering for phase transitions in liquid hydrogen or metal hydrides in a high pressure diamond anvil cell.

He has continued his work on the hard x-ray (1 Å) microprobe using multilayer coated mirrors. He has demonstrated various capabilities of this focusing system. Such a focusing system has high spatial resolution (6 microns in diameter), high intensity ( $10^9$  photons/sec), and a tunable focusing energy when operated on a white synchrotron radiation beamline. It is ideal for high sensitivity x-ray fluorescence microprobing experiments. It has been used to examine interesting samples from a wide selection of disciplines. The system has also examined fluid inclusion in synthetical quartz crystals to demonstrate the usefulness of such a device in determining minor but geophysically important elements that reside in the inclusion. These fluid inclusions are extremely small and buried under the surface, therefore, make the use of other analytical methods extremely difficult if not impossible. The examination of natural fluid inclusion could help to reveal the local geological history. Another class of samples from geological science that this system is uniquely useful for are minerals that contain high concentration of elements with relatively low absorption edges so that they are excited under conventional microprobes (electron microprobe, proton microprobe, and other x-ray microprobes) and their signal overshadows the lower concentration elements

with lower absorption edges. In our case, the excitation can be avoided by simply adjusting the energy of our focused beam. We have also examined some biological and materials science samples.

Another exciting application of microbeam of x-rays is in that of high pressure x-ray diffraction from small samples. Along this line, Yan has continued to work with the group at Carnegie Institution of Washington to perform various x-ray diffraction experiments, to develop necessary skill and knowledge for a successful utilization of the multilayer focusing system in this area. We have examined materials that are important in physics as well as materials that are of particular interest to geology. For example, we have examined the structure of CsI under high pressure. In this experiment, we have reached the highest pressure (302 GPa) at which an x-ray diffraction experiment has been performed, and observed a new phase for CsI. This new structure, closely resembles its isoelectronic, but chemically very distinct neighbor, the rare gas Xe. It demonstrates that the interaction between atoms and the properties of materials under high pressure is extremely different from their ambient pressure form. Further experiments at lower pressure also revealed the mechanism of the phase transition, which helped to resolve a long outstanding controversy in the literature. The high pressures reached and the ability to perform diffraction experiments under these pressures has important application for the understanding of planet earth. For the first time, it is now possible to mimic in the laboratory the extreme pressure and high temperature conditions of the earth's interior. The improvements that can be brought about by the use of a focusing device in these experiments will perform an important role in the high pressure research area in general.

A report on this work was published in a recent issue of Science. Yan Wu has also been involved in experimentation at the Brookhaven National Laboratory's National Synchrotron Light Source, and is expected to participate in experiments at Japan's Photon Factory this winter.

**Kaarin Goncz** is a graduate student in biophysics who has been doing work on x-ray microscopy of enzyme transport in cells and the study of radiation damage in cells. She is preparing to do studies in which the native environment of transport vesicles is modified to induce loss of content as part of the secretion process. She has already begun this work and has a sequence of high resolution x-ray images that indicate that this study will be possible.

**Jonathan Denlinger** is a graduate student in physics using synchrotron radiation to study the surface science and materials science of semiconductor materials. He is studying the formation of the interface between the covalent semiconductor Si and the ionic insulators  $\text{CaF}_2$ ,  $\text{SrF}_2$  and  $(\text{Ca}, \text{Sr})\text{F}_2$  alloys, using x-ray standing wave fluorescence (XSWF) methods. The lattice constants of Si and  $\text{CaF}_2$  are very close (0.5 % difference at room temperature, 1.8% at typical growth temperatures), while that of  $\text{SrF}_2$  is about 7-8% larger (depending on the temperature). Jonathan is probing the onset of lattice relaxation from the Si lattice constant to that of  $\text{SrF}_2$  as a function of  $\text{SrF}_2$  layer thickness on the monolayer scale. An experimental run at Brookhaven's NSLS in August on the  $\text{SrF}_2$  on Si(111) system revealed that the critical thickness for lattice relaxation is between 1 and 2 triple layers of  $\text{SrF}_2$ , and also gave a measurement of the Poisson ratio for an ultra thin film. Also determined was the location of the atoms at the  $\text{SrF}_2$  on Si(111) interface, which has interesting consequences for the question of the subsequent orientation of the  $\text{SrF}_2$  lattice with respect to the substrate. These results will be presented by Jonathan in February at the Physics and Chemistry of Semiconductor Interfaces conference and in March at the American Physical Society meeting.

Jonathan is currently preparing for a second run at NSLS in January 1990 in which we will study the growth of  $(\text{Ca}, \text{Sr})\text{F}_2$  alloys on Si(111). We expect to employ EXAFS in addition to XSWF in this project. This work is being done in collaboration with scientists at AT&T Bell Laboratories.

**Nasif Iskander** is a graduate student in the group studying focusing properties of high resolution fresnel zone plate lenses. Theoretical and computational aspects of his studies include theoretical limits, intensity distributions, the effect of aberrations, and creation of a graphic display capability for visualizing the interplay of these variables. Nasif has been involved in some of our highest resolution laboratory tests of zone plates, as well as in applications.

**Max Wei** is a graduate student in Electrical Engineering and Computer Science who has begun working on reduction x-ray lithography. The goal of this project is to utilize x-ray optics for the reduction of electronic patterns, hoping to achieve feature sizes of  $0.1 \mu\text{m}$  over as wide a field as possible. Initial experiments are planned for early 1990 at the University of Wisconsin's Synchrotron Radiation Center. These experiments also involve collaboration with IBM.

Tai Nguyen is a graduate student in Materials Science and Mineral Engineering. Two major projects on which he is working are transmission electron microscopy studies of x-ray optical multilayers, and fabrication of micron scale slits for hard x-ray applications using thin film technology.

Studies of the tungsten-carbon multilayer system with cross-section high resolution TEM has continued from the previous year and was extended to include lower resolution, plan-view TEM imaging of free standing multilayers, which provide complementary information to that obtained from cross-sectional imaging. In particular, crystalline grain size and phase can be more readily assessed the the plan-view technique. More detailed understanding for the effects of crystallization on annealing were obtained in this study. Observation of tungsten-carbide ( $W_2C$ ) annealing products, together with basic thermodynamics, suggests that multilayers made of alternating layers of tungsten-carbide and carbon, rather than tungsten and carbon, could provide more stable optical structures. Research on this issue was initiated.

Tai's project on fabrication of a micro-scale slit for hard x-rays combining sputtering thin-film technology with cross-sectional sample preparation techniques also progressed. The goal was to use a thin film of low Z material, such as carbon, sandwiched between to thick slabs of high Z material, such as tungsten, in cross section as a slit for hard x-ray experiments requiring a very fine beam. Hard x-ray microscopy, micro-probing, and tomography are examples of such experiments. Traditional slit technology does not work when the slits become smaller than about 10  $\mu m$ : hence the motivation for this unconventional approach. The approach chosen requires much effort to obtain the thin metal film because of large thermal stresses in the film. Because of these difficulties, this approach was deemed unfeasible. No functional slits were obtained. From this experience new ideas for simplified fabrication of micron slits were derived that will be pursued in the future.

Hi resolution TEM studies of multilayers of interest for x-ray optics made of other constituent materials were initiated. Studies of the molybdenum/silicon system together with the ruthenium/carbon system were initiated. Mo/Si multilayers are of demonstrated interesting in EUV optics, and Ru/C multilayers are of potential interest for high normal incidence reflectance above the Si L edges, where the



performance of Mo/Si multilayers falls. Comparisons of observations made from various systems will enable us to make more general conclusions about the structure and stability of x-ray optical multilayers that are made by the sputtering technique.

**Mark Thomas** is an undergraduate physics student involved in the development of a user friendly MS-DOS program to compute and display mirror reflectivities from atomic/molecular surfaces, transmission efficiencies of filters, and other optical constants for 30-10,000 eV x-ray region for the first 92 elements.

This program is already used by many researchers involved in designing synchrotron radiation beam lines throughout the world. This work had been accepted for publication in Nucl. Inst. and Methods, and is also available as Lawrence Berkeley Report LBL-27668 (August 1989).

Mark also participated in fabricating and characterization of sputtered multilayers and performed calculations for novel multilayers for the 1-2 keV x-ray region. He also participated in analyzing x-ray absorption and emission data obtained at Brookhaven National Laboratory's NSLS X-24A beam line.

**Victor Liu** has been an undergraduate student assistant with the Center for X-Ray Optics for almost a year. He assisted in the disassembly and relocation of several delicate experimental systems and helped to restore them to operation. He also contributed to the building and testing of the control system for the x-ray microprobe experiment, which involved motor control, interlock systems, and the software development required for computer control interfacing. He has also been involved in the rebuilding of the our flat crystal x-ray spectrometer, which required him to learn electronic and computer control systems, high vacuum and mechanical systems, and radiation and high voltage safety systems. We anticipate that he will also be involved with the high resolution spectrometer in the next year.

**Erik Bollt** continues to provide useful computational support for our work in synchrotron radiation and free-electron lasers. His recent project has been to study various mirror-hole-aperture configurations for the FEL optical cavity. The eventual goal of this project is to find an optimized cavity out coupling scheme and to determine its loss. He has written a versatile computer program that calculates the mode profile and losses for a general cavity configuration, which will be useful

for designing an FEL cavity. He is currently bench-marking the code with known results.

Jeffrey Davis has continued to work on updating the atomic scattering factors for the elements  $Z = 1$  to 90 in the energy range 10 eV to 10 keV. This work was reported in an LBL report and was presented at the VUV9 conference this summer. Jeff has also worked on developing software that makes use of the scattering factor tables for both microvax and IBM PC computers. He has also collaborated on a Monte Carlo simulation of solid xenon photocathodes, which was also presented at the VUV9 conference.

Jon Chun has worked with us for the past year and has become familiar with vacuum deposition and thin films by sputtering and evaporation and has constructed a variety of x-ray filters. He has also gained experience in data acquisition using a PC and has written programs to monitor film thickness during sputtering using a quartz crystal microbalance and a PC to communicate with a multichannel analyzer.

#### Some Student Publications:

J. Denlinger, M.A. Olmstead, E. Rotenberg, J.R. Patel, and E. Fontes, X-Ray Standing Wave Studies of  $\text{SrF}_2$  on Si(111), SSRL Users Meeting, 1989.

J. Denlinger, M.A. Olmstead, E. Rotenberg, J.R. Patel, and E. Fontes, Atomic Positions and Relaxation at a Lattice-Mismatched Semiconductor-Insulator Interface:  $\text{SrF}_2/\text{Si}(111)$ , PCSI-17, abstract, 1989.

B.L. Henke, J.C. Davis, E.M. Gullikson, and R.C.C. Perera, A Preliminary Report on X-Ray Photoabsorption Coefficients and Atomic Scattering Factors for 92 Elements in the 10-10,000 eV Region, Lawrence Berkeley Laboratory report LBL-26259 (1988).

B.L. Henke, J.C. Davis, E.M. Gullikson, and R.C.C. Perera, Revision and Extension of the 1982 Tables of the Atomic Low Energy Scattering Factors, Presented at the Ninth International Conference on Vacuum Ultraviolet Radiation Physics, 17-21 July 1989 (Paper 13.24).

E.M. Gullikson and J.C. Davis, High Sensitivity Soft X-Ray Photocathodes Using the Rare Gas Solids. Presented at the Ninth International Conference on Vacuum Ultraviolet Radiation Physics, 17-21 July 1989 (Paper 18.41).

H.K. Mao, Y. Wu, R.J. Hemley, L.C. Chen, J.F. Shu, and L.W. Finger, X-ray Diffraction to 302 Gigapascals: High-Pressure Crystal Structure of Cesium Iodide, Science, 246 (1989) 649.

T.D. Nguyen, R. Gronsky, and J.B. Kortright, High Resolution Electron Microscopy Study of As-Prepared and Annealed Tungsten-Carbon Multilayers, Proc. Mat. Res. Soc., 139 (1989) 357.

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H. Rarback, C. Buckley, K. Goncz, H. Ade, E. Anderson, D. Attwood, P. Batson, S. Hellman, C. Jacobsen, D. Kern, J. Kirz, S. Lindaas, I. McNulty, M. Oversluizen, M. Rivers, S. Rothman, D. Shu, and E. Tang. The Scanning Transmission Microscope at the NSLS, Nucl. Instru. and Methods, in press.

M.M. Thomas, J.C. Davis, C.J. Jacobsen, and R.C.C. Perera, A Program for Calculating and Plotting Soft X-Ray Optical Interaction Coefficients for Molecules, presented at SRI '89 in Berkeley, CA August 1989.

Y. Wu, H.K. Mao, R.J. Hemley, L.C. Chen, J.F. Shu, and L.W. Finger, Crystal Structure and Equation of State of CaI<sub>2</sub>, abstract submitted for the March 1990 Meeting of the American Physical Society.

Y. Wu, A.C. Thompson, J.H. Underwood, R.D. Giaque, K. Chapman, M.L. Rivers, and K.W. Jones, A Tunable X-ray Microprobe Using Synchrotron Radiation, Nucl. Instru. and Methods, in press.

## Appendices

### (A) Development of Fourier Transform X-Ray Holography

Janos Kirz  
Physics Department  
SUNY Stony Brook, NY

During the past year the project to develop Fourier transform holography has progressed on several fronts:

An advanced CCD camera was constructed using a Thompson CSF CCD detector with  $^{31}\text{P}$  phosphor coating to transform the x-ray signal to visible light. Electronics for the read-out were built and tested. The camera includes a thermoelectric cooler to cool the chip to  $-40^{\circ}\text{C}$  and thereby reduce the dark current. The CAMAC-based electronics transfer the image to the VAX station 3200 for storage, display, and analysis. The camera has an aluminized silicon nitride window to admit soft x-rays but not visible light. It is evacuated to a pressure of 10 millitorr using a sorption pump.

The detective performance of the first generation CCD camera was analyzed. The system noise is about 50 electrons, and when cooled to  $-40^{\circ}\text{C}$ , the dark current is about 10 electrons/pixel/second. Though sufficient for obtaining first results, these figures will need reduction to record high quality holograms. Improved electronics and liquid nitrogen cooling are under development to reduce the noise.

Dr. Erik Anderson of the Lawrence Berkeley Laboratory Center for X-Ray Optics, using the facilities of the Nanostructure Fabrication Group at the IBM Research Center, fabricated high resolution fresnel zone plates and custom test objects for the project. The test objects have feature sizes down to the expected resolution of the apparatus.

The zone plates and test objects were tested at the NSLS undulator beamline X1A, using the scanning transmission x-ray microscope. Images of the test objects indicate that the zone plates perform according to design. Test objects fabricated in the future will need to have the region surrounding the test pattern plated thicker to obtain holograms of good contrast.

The entire system, including zone plate, test object, and CCD camera were tested and aligned on the A1A beamline. Although no holograms of the test objects were

recorded on this first test, interference fringes for the pinhole collimator were observed.

Results were presented in poster papers at the NSLS Annual Users Meeting in May 1989, and at the Synchrotron Radiation Instrumentation Conference in Berkeley California in August 1989.

Graduate student Ian McNulty did much of the work under the direction of the principal investigator. Mr. McNulty will continue with the work for his Ph.D thesis.

The development of Fourier transform holography is continuing with an increased level of support for the DOE Office of Health and Environmental Research.

#### Publication

I. McNulty, J. Kirz, C. Jacobsen, E. Anderson, M.R. Howells, and H. Rarback, Soft X-Ray Microscope Using Fourier Transform Holography, in press.

## **(B) Reflective Optics**

**M.C. Richardson**  
**University of Rochester, Rochester, NY**

We continue to make progress in the development of curved multilayer x-ray optics for applications to point x-ray sources. Our efforts in the past year have been placed in four areas.

**(a) Multilayer coating facility.** The final assembly and testing of this facility was completed in 1988. Initial test multilayer coatings of Si/C layers were made to test the uniformity and reproducibility of layer thickness with system parameters before the facility was moved from a building on campus to a new wing of LLE. The facility is part of the University of Rochester's Coating Laboratory, which was transferred in 1988 from the Institute of Optics to LLE. Although the x-ray multilayer facility has been re-established, there are doubts about its continued operation. Its operation is partially funded by the contract LLE has with DOE for inertial fusion work. In addition the facility's principal operator, Cindy Hayden, left the employment of LLE in August 1989.

**(b) Ultra-short laser-produced x-ray pulse development.** Previous reports have described our initial investigations of plasmas produced by high-intensity ( $>10^{15}$  W/cm<sup>2</sup>) ultrashort (1 psec) laser pulses. New experimental studies in this area have been delayed by the need to move the laser system and target facility used in these studies from one laboratory to another within LLE. This has largely been completed and target experiments should commence in the near future.

**(c) X-ray point source in exploding wire geometry.** We have recently established a collaboration with Professor David Hammer and his group at the Plasma Science Laboratory at Cornell University. This group is investigating point x-ray sources from exploding cross-wire targets energized by the 0.1-TW LION ion diode machine, as possible sources for photo pumped x-ray laser schemes. We have helped in these studies by fielding x-ray imaging and spectroscopic instrumentation to determine the x-ray fluence from the exploding wire targets. In addition we have used this x-ray source to make initial characterization measurements of a new Kodak film (uncoated T-MAX 3200) which is sensitive in the soft x-ray and EUV range. In direct comparisons with Kodak 101-06 film, the new film exhibited reduced sensitivity (by about a factor of 4 in the 50 Å region, with lowering sensitivity for longer wavelengths). No measurements were made of the resolution or the dynamic range.

(d) **Multilayer Schwarzschild optics at 44Å.** Following our success in demonstrating normal incidence x-ray imaging of a point source at 44Å with a simple spherical mirror [1], we are now investigating superior optical elements. Foremost among these objectives is the improvement in collection power and in spatial resolution. As an initial test we are experimenting with a commercially available Schwarzschild objective (Ealing 15X reflecting objective).

This objective has a numerical aperture of 0.3 and an object distance of 13 mm. A pair of unsilvered glass mirrors have been coated with 3s W/C layers having 2d spacing of 44.18Å. Account was made for the difference in angle of the two mirrors in coating the mirrors for maximum reflectivity at 44.15 Å. The mirror combination is currently being assembled and aligned into a vacuum-compatible mount.

It will shortly be tested in initial experiments with plasmas produced by ultrashort (elps) laser pulses.

#### Reference

[1] C. M. Brown, U. Feldman, J. Seely, M. C. Richardson, H. Chen, J. Underwood, and A. Zeigler, Opt. Comm. 08, 190 (1988).

Student Participation: Hong Chen (Physics, graduate student),  
University of Rochester



### **(C) Computer Simulation of XUV Systems**

**F. Cerrina**  
**Center for X-ray Lithography**  
**University of Wisconsin, Stoughton, WI**

The development of the modeling code has progressed along the lines described in the statement of work. The code is in phase of advanced development and is undergoing final debugging before shipment to CXRO. In particular we have:

- 1. Implemented a wavefront analysis routine based on the use of least square fitting.** The original approach, based on the use of an actual fitting routine, was soon abandoned because the non-orthogonal nature of the power series may lead easily to singular matrices. We decided to use instead an approach based on the use of orthogonal polynomials. The algorithm selected is based on the use of Zernicke polynomials for circular apertures and of Legendre polynomials for rectangular systems. The use of orthogonal polynomials reduce the computational load and improves the convergence of the process. The procedure adopted is the following: a screen is located at the systems exit aperture and SHADOW is run selecting the option of computing the optical path, which is stored in a suitable array, for example in function of the converging angles. The code reads the file and expands the resulting function in polynomials; the aberration coefficients are well known and algebraic expression exists to change between the two bases. The results are presented in the form of coefficients of the power series and of the polynomial used to expand the path function.
- 2. Developed the algebraic expansion for a system of one and two mirrors.** It is complete and working; testing will begin shortly, before delivery. The program correctly predicts the aberration expansion of toroidal and elliptical mirrors, on the basis of published work (in particular Namioka's papers). Diffraction gratings aberrations are predicted correctly, as well, up to the fifth order. The program was originally based on the use of SMP; unfortunately the high cost of running the program has made it impossible for us to complete the development. We have been hampered by the lack of computational resources; this has been recently overcome thanks to the acquisition of two VAX systems. We have, as well, acquired two copies of Mathematica, one for the VAX and the other for the IBM PC, so that we expect to restart soon the development work and to finish the expansion. The approach is indeed proving to be extremely powerful and capable of helping in the design of optical systems.

3. **Implemented a large part of the calculations of the surface roughness in SHADOW and the program is being documented.** The approach is based on the analysis of Bennett, Church and on the earlier work of Beckmann and Spizzichino. SHADOW reads a file containing the power series specifying the roughness and uses it to implement a "random grating" to compute the scattered directions. This part of the code has not been fully developed yet, but we expect to have it completed soon.

The code development is essentially completed, while the documentation writing and the final debugging and certification have not been completed yet. We expect that all the work will be completed during the last quarter of 1989.

The students involved have also developed a significant fraction of the documentation supporting SHADOW. As a side result that may be of interest to the sponsoring agency, we like to report that we have recently acquired (independently from the present grant) a software package called IDL for data analysis and visualization. The package is extremely powerful and capable of displaying directly output from SHADOW. It can perform also complex calculations and prepare presentation graphic quality plots on a variety of different plotting devices. It is highly recommended.



# *Applied Science and Technology*

*College of Engineering · University of California at Berkeley*

## UNIVERSITY OF CALIFORNIA

### Program in Applied Science and Technology

#### Programs of Study

The Program in Applied Science and Technology (AS&T) is an interdisciplinary one involving the application of emerging technological and mathematical developments to fundamental and applied aspects of the physical and life sciences. Major areas of emphasis include applied physics, mathematical sciences, technological applications to the life sciences, and other topics in which a cross-disciplinary environment is beneficial. In addition to its own courses, the program draws strength from several established departments of the U.C. Berkeley campus, as well as from research opportunities at the adjacent Lawrence Berkeley Laboratory (LBL).

The program supervises student academic and research activity leading to both the Master of Science and Doctor of Philosophy degrees. A Faculty Executive Committee is responsible for the overall administration of the program. Each student will have a Graduate Advisor who will help develop an appropriate course of study. The Faculty Executive Committee within Applied Science and Technology will be responsible for admissions, student progress, curriculum content and degree requirements. Because of the interdisciplinary nature of the program, and the anticipated diversity of student backgrounds and interest, a sequence of courses satisfying University and department requirements, but relevant to the program, will be established individually for each student.

#### Thesis Subject Areas

Current faculty research pursuits include topics from all three areas: applied physics, mathematical sciences, and applications in the life sciences. From applied physics topics include: generation of partially coherent short-wavelength radiation, x-ray optical techniques applied to the physical and life sciences, accelerator physics and technology, free-electron devices, plasma physics, plasma assisted materials processing, application of microscopy, spectroscopy and diffraction to probe the atomic structure and chemistry of interfaces between dissimilar materials, layered and laminated materials, chemical, physical, and electronic properties of interfaces, various topics in quantum electronics and nanostructure fabrication. In mathematical sciences, topics include: nonlinear dynamics, numerical methods, computational fluid mechanics and turbulence theory, with possible applications to physical, biological and chemical systems. Also included are such topics as computer graphics, medical imaging, inverse problems in geophysics, and flame propagation. In the life sciences topics include: application of microscopies and spectroscopies to living organisms, dynamical studies of cellular processes, biochemistry and biophysics of membrane transport, cellular response to stress, intracellular spatial

resolution of chemical substances and regulation of metabolic processes.

#### **Research Facilities**

Faculty members are involved with many state-of-the-art experimental laboratories on the Berkeley campus and within the Lawrence Berkeley Laboratory (LBL). Among the unique facilities at LBL are the National Center for Electron Microscopy, which houses the highest-resolution electron microscope in the world; the Center for X-ray Optics; and presently under construction, the Advanced Light Source, a next-generation synchrotron facility of extremely high brightness and coherent power at UV and x-ray wavelengths. The program has access to the many excellent libraries on the Berkeley campus, and to powerful computational resources at both sites. In addition to utilizing several important research facilities on the Berkeley campus, including materials preparation and diagnostics, optical laser facilities, and plasma processing laboratories, the group also participates in joint research programs in cell physiology with the University of California at San Francisco.

#### **Financial Aid**

Students are encouraged to apply for Regent's fellowships administered by the University. Research assistantships are available in projects supported by extra-mural grants or contracts. An effort is made to align the research assistant's interests with those of his or her faculty supervisor. Many research assistants work half-time during the academic year and full-time during part of the summer.

#### **Cost of Study**

Fees, insurance and tuition for 1989-90 total approximately \$1900 for state residents, and \$7700 for non-residents. Costs for 1990-91 are expected to be slightly higher.

#### **Cost of Living**

Room and Board in the San Francisco Area for the nine-month academic year averages \$4500-\$6500. Books and supplies total about \$400, and entertainment and miscellaneous expenses about \$1200. Costs are proportionately higher for the twelve-month academic year.

#### **A New Program**

Applied Science and Technology is a new program on the U.C. Berkeley campus, operating under the auspices of the College of Engineering's Interdisciplinary Studies Center. Until the new program is formally approved by the University, it will be supervised by an Applied Science and Technology Faculty Executive Committee appointed by the Dean, College of Engineering. Normal departmental support to students will be

through the office of Dean Edwin Lewis, Associate Dean for Interdisciplinary studies. Student programs will be coordinated closely with one of Berkeley's established departments during the program approval process. They will remain students in that department for degree-granting purposes until final approval of the new graduate group is secured. Subsequently, application for admission to the group will be either directly or through a department. The coordination will be done by Dean Lewis and the Applied Science and Technology Faculty Executive Committee.

### **The University**

The campus is surrounded by the suburban city of Berkeley (population 110,000) at the foot of the wooded Berkeley hills. The San Francisco Bay Area, a nine-county region, is widely acclaimed for its cultural resources, such as museums, galleries, symphony orchestras, opera company, and theater. Coffee houses and restaurants abound. The campus and large student community provide a stimulating atmosphere through numerous public lectures, concerts, dramatic presentations, and exhibits. A number of nearby regional parks offer rural serenity.

Within the campus are redwood groves, plazas, and picturesque Strawberry Creek, which runs the length of the campus, giving a parklike atmosphere. Many areas of the campus provide a panoramic view of the San Francisco Bay Area. Berkeley is the oldest of the nine campuses of the University of California, founded in 1868. Berkeley continues to create new programs and services as it adapts to new needs and trends in an effort to make higher education one of the most exciting and meaningful experiences. U.C Berkeley is consistently rated among the top academic institutions in the United States.

### **Student Group**

Approximately 30,000 students, including close to 9,000 graduate students are enrolled in Berkeley. The cosmopolitan student body includes about 1,900 foreign students from nearly ninety countries and about 3,500 students from states other than California.

### **Applying**

Applications for the fall 1990 semester are due February 1, 1990. Applications materials are available through the address below. Students are requested to include GRE scores.

### **Correspondence and Information**

Program in Applied Science and Technology  
230 Bechtel Engineering Center  
University of California  
Berkeley, California 94720  
Telephone: 415-642-8790

Faculty associated with the Program in Applied Science and Technology

T. Ken Gustafson (Electrical Engineering and Computer Sciences, UCB;  
Quantum Electronics Group, UCB; Center for X-ray Optics, LBL)  
Modern optics and quantum electronic techniques applied to signal processing, computation and materials studies. The investigation of nonlinear optical phenomena and in particular thresholding and optical logic devices, x-ray optical techniques applied to nanostructure fabrication.  
(tkg@janus.berkeley.edu)

David Attwood (Applied Science and Technology, UCB;  
Center for X-ray Optics at LBL)  
Partially coherent radiation at short wave-lengths, synchrotrons, undulators, x-ray lasers, processes in hot dense plasmas; x-ray optics, microscopes, and holography; application of element specific x-ray microscopy to studies in the life and physical sciences.  
(attwood@lbl.gov)

Stanley A. Berger (Mechanical Engineering, UCB)  
Theoretical and numerical analysis of large and small Reynolds numbers flows, incompressible and compressible. Physiological fluid mechanics.

Charles Birdsall (Electrical Engineering and Computer Sciences, UCB;  
Plasma Interdisciplinary Committee, UCB)  
Plasmas; plasma theory and many-particle simulations; applications ranging from fusion plasmas to plasma assisted materials processing; current emphasis is on plasma-sheath-surface dynamics.  
(birdsall@janus.berkeley.edu)

Alexandre Chorin (Mathematics Department, UCB)  
Computational fluid mechanics and turbulence theory.

Leon O. Chua (Electrical Engineering and Computer Sciences, UCB)  
Nonlinear circuits, Nonlinear systems, bifurcation theory, chaos, neural networks. CAD and Non-linear electronics.  
(chua@esvax.berkeley.edu)

Lutgard C. DeJonghe (Material Science and Mineral Engineering, UCB  
Center for Advanced Materials, LBL)  
The science of ceramic processing. Particulate composites of ceramics with polymer, metal or ceramic matrix. Microstructure characterization.

Roger W. Falcone (Physics Department, UCB)  
Quantum electronics and short wavelength coherent light sources, with applications to atomic physics, solid state physics and plasma physics.

Ronald Gronsky

(Materials Sciences and Mineral Engineering, UCB;  
National Center for Electron Microscopy, LBL)

Identification of atomic structure of interfaces and defects in materials using techniques of electron microscopy. Relationship between atomic structure and properties of metallic alloys, ceramics, semiconductors, and superconductors, including the superconducting oxides with high T<sub>c</sub>.  
(rgronsky@lbl.gov)

F. Alberto Grunbaum

(Mathematics Department, UCB)

Image reconstruction. Tomographic methods in medicine, geophysics, nondestructive evaluation. The mathematics and physics of solitons, applications to signal processing.

Yuan T. Lee

(Chemistry, UCB;  
Materials and Chemical Sciences Division, LBL)

Laser induced photochemical processes.

Allan J. Lichtenberg

(Electrical Engineering and Computer Science, UCB;  
Nonlinear Systems and Dynamics Group and  
Interdisciplinary Plasma Committee, UCB)

Nonlinear dynamics with applications to plasmas and particle accelerators. Plasma confinement, heating and fusion. Plasma discharges for materials processing.

Michael A. Lieberman

(Electrical Engineering and Computer Science, UCB;  
Nonlinear Systems and Dynamics Group and Interdisciplinary  
Plasma Committee, UCB)

Plasmas and non-linear dynamics, both theory and experiment. Applications to integrated circuit fabrication. Chaos and bifurcations in dynamical systems, optical and quantum chaos, chaos in non-linear circuits.

(lieber@janus.berkeley.edu)

Robert Macey

(Molecular and Cell Biology, UCB;  
Applied Science Division, LBL)

Research on basic mechanisms of membrane transport using the red blood cell as a prototype: current work focuses on transport of water, urea and the electrostatic barriers imposed by the lipid bilayer. Research on pathological red cells: current work focuses on the hydration of sickle cell anemiared cells, basic osmotic properties and the fate of red cells in inhospitable environments, and in the kidney, liver and lungs. Methods include EPR and fluorescent spectroscopy, fast kinetics, and the development of mathematical models.

Philip S. Marcus

(Mechanical Engineering, UCB;  
Nonlinear Dynamics Group)

Bifurcations and development of chaotic flows, numerical simulation of three-dimensional fluid flow, vortex dynamics, numerical algorithms for large Reynolds number flows, applications to astrophysics and geophysics.



Jerrold E. Marsden (Mathematics, UCB;  
Nonlinear Dynamics Group)  
Nonlinear dynamics, Hamiltonian structures, stability, geometric methods in mechanics, including Berry's phase, general relativity and chaotic dynamics.  
At Cornell (marsden@mathvax.msi.cornell.edu)  
At Berkeley (marsden@math.berkeley.edu)

C. Bradley Moore (Chemistry, UCB)  
Laser-induced chemistry and laser probes of complex reaction systems.

George Oster (Molecular and Cell Biology, UCB)  
Theoretical understanding of cellular structure with particular emphasis on morphogenesis.

Alexandre Quintanilha (Molecular and Cell Biology, UCB;  
Applied Science Division, LBL)  
Oxidative and antioxidative cellular mechanisms, general cell stress and defense mechanisms, the role of sulphur in regulating enzymatic activities in cells, spectroscopic techniques applied to intracellular and membrane dynamic processes.

Arthur Rosenfeld (Physics Department, UCB)  
Center for Building Science, Applied Science Division, LBL)  
Physics applied to efficient use of energy, particularly in buildings; utility planning for least cost energy services; energy policy; data and document bases of conservation technologies and programs; CAD for efficient buildings.

Stephen Rothman (Physiology, Biophysics, Bioengineering, UCSF;  
Center for X-ray Optics at LBL)  
Cell Physiology and biodynamics with particular interest in high resolution imaging of biological cells and unaltered substructure with soft x-rays. Applying soft x-ray microscopy and other imaging methods to follow dynamics at the ultrastructural and supramolecular level. Permeability of to protein molecules.

James Sethian (Mathematics Department, UCB)  
Numerical methods, scientific computing, partial differential equations, computational differential geometry, parallel processing, scientific visualization, computer graphics, and mathematical modeling.  
(sethian@think.com)

Shyh Wang (Electrical Engineering and Computer Science, UCB;  
Quantum Electronics Group and Solid State Group, UCB)  
Heteroepitaxy by molecular beams; studies of electronic and optical properties of semiconductors, heterostructures and interfaces; applications to lasers and electronic devices of compound semiconductors; and application of electron-optical probing techniques to material and device studies.

Alan Weinstein

(Mathematics, UCB;  
Nonlinear Dynamics Group)

Symplectic geometry, Hamiltonian structures, stability, connections between classical and quantum mechanics.  
(alanw@math.berkeley.edu)

12/19/89

## Graduate Studies in Applied Science and Technology

### Emphasis in Applied Physics

Graduate students in AS&T choosing to emphasize studies in Applied Physics will be expected to complete a sequence of courses which cumulatively provide a firm foundation in an area of applied physics which combines material from a combination of physics and engineering, materials science and mathematics. They will also be expected to participate in research activities which familiarize them with the state of the art technologies, in such areas as nanofabrication, materials characterization, generation of short wavelength radiation, etc. The selection of appropriate course sequences, taking into account the students background, should be done with the approval of the Graduate Adviser, and with approval of the AS&T Faculty Executive Committee. Depending upon the student's academic background, courses might be chosen from the following list:

Physics	110A, B	Electromagnetism and Optics
Physics	137A, B	Quantum Mechanics
Physics	141A, B	Solid State Physics
Physics	180	End Use of Energy
Physics	210A, B	Theory of Electricity and Magnetism
Physics	211	Equilibrium Statistical Physics
Physics	212	Nonequilibrium Statistical Physics
Physics	221A, B	Quantum Mechanics
Physics	240A, B	Quantum Theory of Solids
Physics	242A, B	Theoretical Plasma Physics
Physics	208A, B	Intro. to Quantum Electronics and Nonlinear Optics
EECS	_____	Basic Principles of Nanolithography and Sub-micron Structures
EECS	117A, B	Electromagnetic Waves and Fields
EECS	130	Integrated Circuit Devices
EECS	131	Semiconductor Electronics
EECS	136	Lasers And Quantum Electronics
EECS	143	Processing and Design of Integrated Circuits
EECS	210A, B	Applied Electromagnetic Theory
EECS	230	Solid State Electronics
EECS	231	Solid State Devices
EECS	236A, B	Quantum and Optical Electronics. or
EECS	237	Quantum Electronics of Solids
EECS	238	Superconductive Devices and Circuits
EECS	239A, B	Plasmas
EECS	290F	Mathematical Methods in Electromagnetic Theory
EECS	290J	Image Processing
EECS	290N, O	Integrated Circuit Technology Design
Math	121A, B	Mathematical Tools for the Physical Sciences
Math	128A	Numerical Analysis
Math	185	Theory of Functions of Complex Variable
Math	220A, B	Applied Math For the Physical Sciences and Engineering
Math	224A, B	Mathematical Methods for the Physical Sciences
Math	228A, B	Numerical Solutions of Differential Equations
Math	273 series	Topics in Applied Math
E	210	Introduction to X-Ray Physics and Technology
E	298A	Applied Sciences and Technology Seminar
IDS	_____	Lasers and Modern Optics
IDS	_____	Radiation and Scattering at Short Wavelengths
IDS	_____	Accelerator Physics and Technology
IDS	_____	Free Electron Lasers

IDS	—	Introduction to Plasma Physics
IDS	—	Surfaces, Thin Films and Interfaces
IDS	—	Applications of Spectroscopy to Biological Systems
IDS	—	Applied Sciences and Technology Laboratory
MSE	102	Bonding, Crystallography, and Crystal Defects
MSE	102	Crystallography and Crystal Defects
MSE	111	Electrical and Magnetic Properties of Materials
MSE	122	Ceramic Processing
MSE	123	Semiconductor Processing
MSE	202	Crystal Structure and Bonding
MSE	204	Electron Microscopy
MSE	223	Semiconductor Materials
MSE	224	Solar Energy Materials
MSE	231	Advanced Electron Microscopy
MSE	241	Electron Microscopy and Microanalysis
MSE	290	Grain Boundary Structure and Properties
Chem Eng	179	Process Technology of Solid State Materials & Devices
	295E	Electrochemical Energy Conversion
	295Q	Thin Film Technology

## Graduate Studies in Applied Science and Technology

### Emphasis in Mathematical Sciences

Graduate students in AS&T choosing to emphasize studies in Mathematical Sciences will be expected to complete a sequence of courses which cumulatively provide a firm foundation in mathematics and its applications to the sciences and engineering. They will also be expected to participate in research activities which familiarize them with state-of-the-art techniques, thus permitting them to make significant contributions in a chosen area in basic applied mathematics. The selection of course sequences, taking into account the students background, should be done with the approval of the Graduate Advisor, and with approval of the AS&T Faculty Executive Committee. Depending upon the student's academic background, courses might be chosen from the following list:

Math	121AB	Mathematical Tools for the Physical Sciences
Math	128AB	Numerical Analysis
Math	170	Linear Programming, games, models of exchange
Math	191	Mathematical methods in classical and quantum mechanics
Math	204AB	Ordinary and Partial Differential Equations
Math	211	Mathematical theory of fluid mechanics
Math	219	Ordinary Differential Equations
Math	220AB	Applied Mathematics for the Physical Sciences and Engineering
Math	221	Advanced Matrix Computations
Math	224	Mathematical Methods for the Physical Sciences
Math	228AB	Numerical Solutions of Differential Equations
Math	273	Advanced Numerical Analysis
Math	275	Topics in Applied Mathematics
EECS	104	Linear and Nonlinear Circuits
EECS	219	Circuit Theory and Computer-Aided Analysis
EECS	220	Nonlinear Circuits
EECS	221A	Linear System Theory
EECS	221B	Multivariable Feedback Theory
EECS	222	Nonlinear Systems Analysis, Stability and Control
EECS	223	Stochastic Systems: Estimation and Control
EECS	226A	Random Processes in Systems
ME	266	Numerical Methods in Fluid Mechanics
ME	260	Waves in Fluids
ME	262	Theory of Fluid Sheets and Fluid Jets
ME	263	Turbulence in Engineering Flows
ME	267	Geophysical Fluid Dynamics
Physics	205A, B	Advanced Dynamics
Physics	231	General Relativity
E	298A	Applied Science and Technology Seminar

## Graduate Studies in Applied Science and Technology

### Emphasis in Life Sciences

Graduate students in AS&T choosing to emphasize studies in technical applications to the Life Sciences will be expected to complete a sequence of courses which, in combination with their research, will provide a firm base of knowledge regarding the chemical, physical, and dynamical characteristics of the biological cell. The research should include an in-depth study of at least one aspect of a biological system. In all cases, students will be expected to participate in research activities that familiarize them with state-of-the-art technologies relevant to basic contributions in the biological sciences at the cellular and sub-cellular level. The selection of appropriate course sequences, taking into account the student's background and interests, will be carried out with the advice and approval of the student's Graduate Advisor. Depending upon the student's background, courses might be chosen from the following list:

Anatomy	105	Histophysiology
MCB	110	General Biochemistry and Molecular Biology
MCB	120	Cell Physiology
MCB	120L	Physiology Laboratory
MCB	122	Biophysics
MCB	130	Biology
MCB	131	Radiation Biophysics
MCB	135D	Cellular Aspects of Development
MCB	135E	Intracellular Signaling
MCB	200	Advanced Biochemistry and Molecular Biology
MCB	201A, B,	Advanced Biochemistry and
		Molecular Biology Laboratory Methods
MCB	203	Structure and Function of Eukaryotic Cellular Membranes
MCB	206	Physical Biochemistry
MCB	213	Structure and Function of the Prokaryotic Cell
MCB	218D	DNA Structure and Function
MCB	220B	Membrane and Lipoprotein Structure and Dynamics
MCB	220E	Free Radicals and Oxygen Toxicity in Biology
MCB	239Z	The Cytoskeleton and Morphogenesis
MCB	241	Structural Biophysics
PB	100A	Molecular, Cellular and
		Genetic Aspects of Plant Development
PB	100B	Physiology and Biochemical Plant Biology
PB	222	Photosynthesis
E	210	Introduction to X-ray Physics and Technology
E	298A	Applied Science and Technology Seminar
IDS	200A	Cellular Neurobiology
IDS	—	Applications of Spectroscopy to Biological Systems
IDS	—	Topics in Cell Physiology
IDS	—	Analysis of Specific Research in Biology
MSE	204	Electron Microscopes
MSE	231	Advanced Electron Microscopes